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Forces Generated by High Velocity Impact of Ice on a Rigid Structure

J. Michael Pereira, Santo A. Padula, II, Duane M. Revilock, and Matthew E. Melis
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Abstract

Tests were conducted to measure the impact forces generated by cylindrical ice projectiles striking a relatively rigid target. Two types of ice projectiles were used, solid clear ice and lower density fabricated ice. Three forms of solid clear ice were tested: single crystal, poly-crystal, and "rejected" poly-crystal (poly-crystal ice in which defects were detected during inspection.) The solid ice had a density of approximately 56 lb/ft^3 (0.9 gm/cm^3). A second set of test specimens, termed "low density ice" was manufactured by molding shaved ice into a cylindrical die to produce ice with a density of approximately 40 lb/ ft^3 (0.65 gm/cm^3). Both the static mechanical characteristics and the crystalline structure of the ice were found to have little effect on the observed transient response. The impact forces generated by low density ice projectiles, which had very low mechanical strength, were comparable to those of full density solid ice. This supports the hypothesis that at a velocity significantly greater than that required to produce fracture in the ice, the mechanical properties become relatively insignificant, and the impact forces are governed by the shape and mass of the projectile.

Introduction

Damage produced by ice impacting structures is a common phenomenon. It can be observed on aircraft canopies, automobiles after hail storms, in jet engines and on compressor blades in ground based turbine electrical generators. The damage caused by the potential impact of ice is also a concern to NASA's Space Transportation System (Space Shuttle) and great care is taken to document and characterize any ice formations that occur on the external tank prior to launch (ref. 1). The potential of ice impacts on the Space Shuttle has recently taken on greater importance after the loss of the Space Shuttle Columbia during re-entry into Earth's atmosphere on February 1, 2003. It was determined that the cause of the accident was a breach in the leading edge thermal protection system, caused by the impact of a piece of insulating foam during launch, which allowed superheated air to penetrate the leading edge insulation and progressively melt the aluminum structure of the left wing (ref. 2). After the cause of the accident was determined, an intense effort was undertaken by NASA to characterize and mitigate the risks associated with impacts of any potential launch debris, one of them being ice. A significant part of NASA's effort consisted of developing improved numerical simulation capabilities to allow the prediction of damage caused by potential debris.

The properties of ice are highly dependent on temperature, strain rate, density and crystalline structure (refs. 3 and 4). In general, the forces generated during impact may also depend on these factors, as well as on the impact velocity and shape of the ice projectile. The impact velocity range of concern during launch of the Space Shuttle is from approximately 300 to 800 ft/sec. The type of ice that forms on the external tank of the shuttle ranges from fully dense solid ice to frost, but for the purpose of developing numerical impact models it was considered appropriate to study what was considered to be the worst case, which is that of fully dense ice.

This report documents an effort that was conducted to measure the forces generated by ice projectiles of different structural and crystalline makeup impacting a rigid structure at various velocities and orientations. The data was used to characterize the physics of ice impact and validate the numerical models of ice.

Methods

Initial Observations

When a fully dense, clear piece of ice impacts a relatively rigid structure at a high velocity, fracture immediately occurs at the impact point on the ice. The stress front travels through the ice, at a velocity which can be estimated from the material properties of the ice, fracturing the ice as it travels. If the impact velocity of the projectile is significantly less than that of the speed of the fracture wave, other than the initial stress which produces the fracture, the projectile becomes a mass of particles, with the same overall mass and density of the initial solid ice, but with little mechanical strength. It can be hypothesized that the mechanical properties of the ice therefore become less important and, as the velocity increases, the forces that are developed depend mainly on the mass of the ice. While the force required to initially fracture the ice is present, it becomes less significant relative to the total force.

Initial experiments conducted to observe the propagation of damage in ice projectiles demonstrated this phenomenon. Figure 1 shows a sequence of images taken at the time of impact of a 1.25-in.-diameter, 3-in.-long solid ice cylinder impacting a steel plate at a speed of 680 ft/sec. These photographs were taken at a frame rate of 260,010 frames/sec. The velocity of the fracture wave was approximately 8,000 ft/sec and the time taken to fully fracture the ice specimen was approximately 19×10^{-6} sec. During the time it took for the fracture wave to completely traverse the specimen, the back of the projectile traveled 0.16 in.

Impact Force Measurement

Impact tests were conducted to measure the impact forces generated by cylindrical ice projectiles striking a relatively rigid target. Two types of ice projectiles were used in this study, solid clear ice and lower density fabricated ice. The solid ice projectiles were cylinders machined to a diameter of 11/16 in. and a length of 1.66 in. from blocks of clear carving ice by Ice Culture (Hensall, Ontario). Prior to testing the crystalline structure of each ice projectile was characterized by Schulsen (ref. 5). Three forms of solid clear ice were tested: single crystal (SX), poly-crystal (PX) and rejected poly-crystal (RPX). The latter

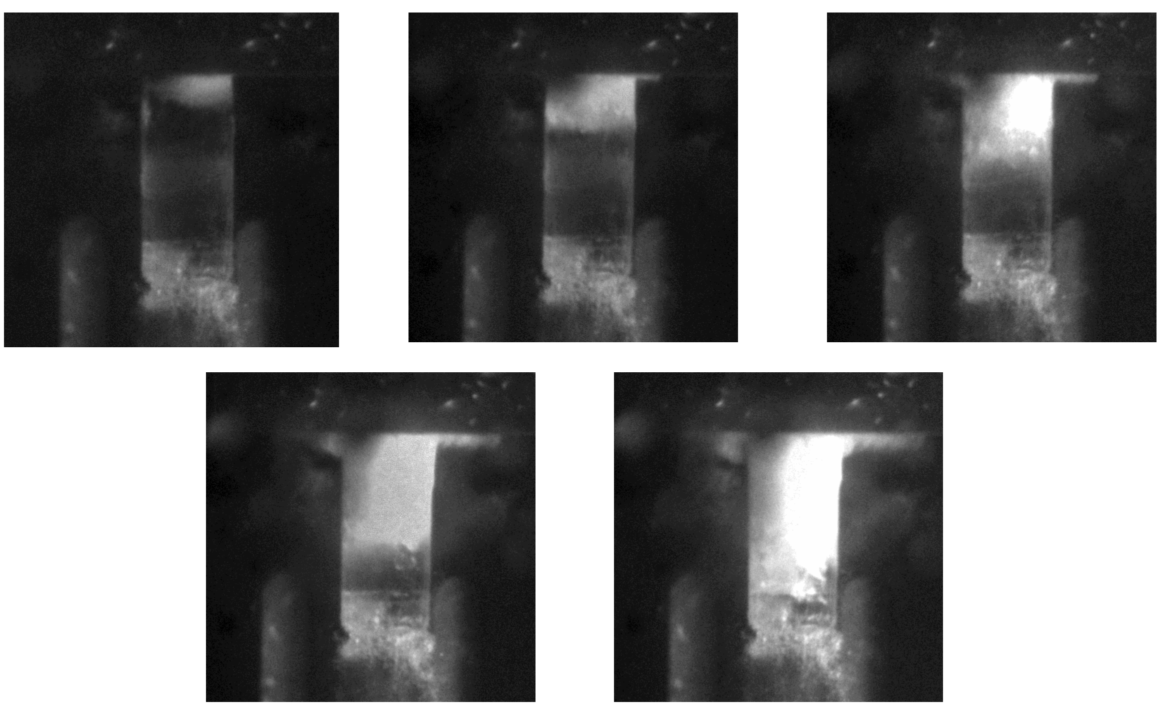

Figure 1.—Sequence of photographs showing a cylinder of fully dense ice impacting a steel plate at 700 ft/sec.

was termed “rejected” due to the presence of defects detected during inspection. The solid ice had a density of approximately 56 lb/ft^3 (0.9 gm/cm^3). A second set of test specimens, termed “low density ice” was manufactured by molding shaved ice into a cylindrical die to produce ice with a density of approximately 40 lb/ ft^3 (0.65 gm/cm^3). Examples of low density and full density ice projectiles are shown in figures 2 and 3, respectively.

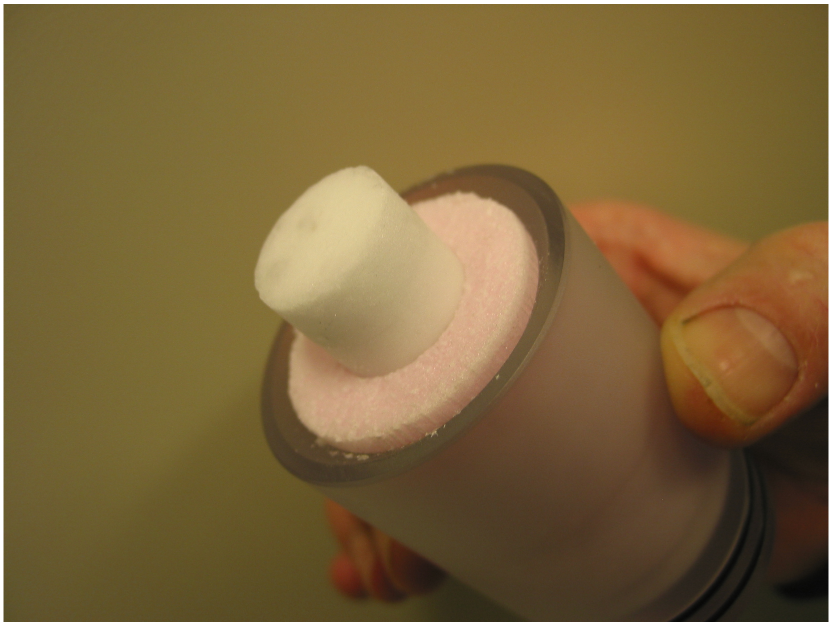

Figure 2.—Polycarbonate sabot containing a low density ice projectile supported in rigid foam.

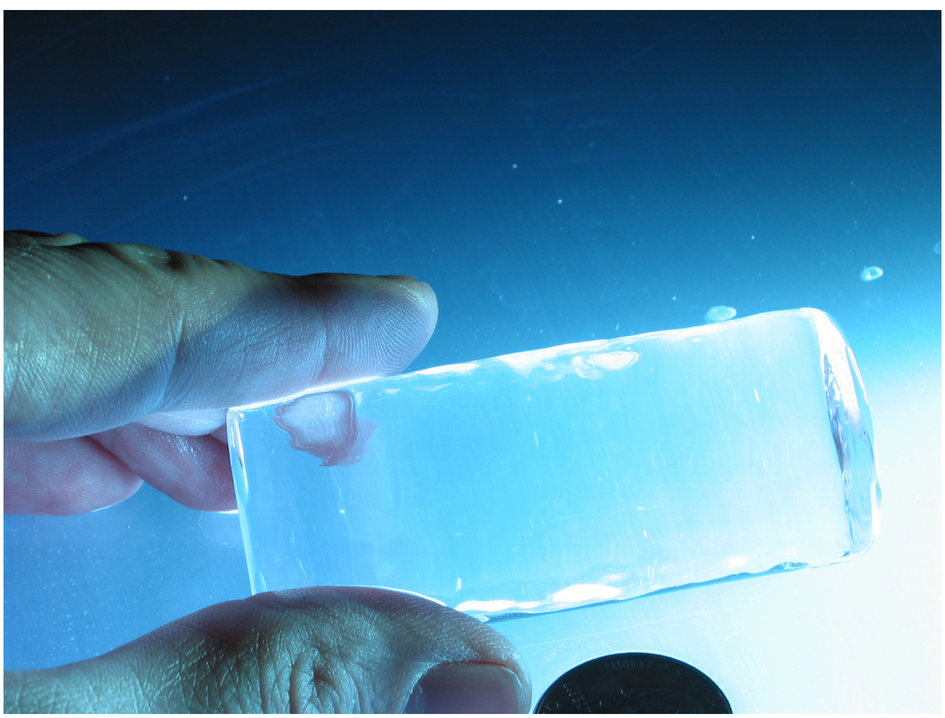

Figure 3.—Full density ice projectile.

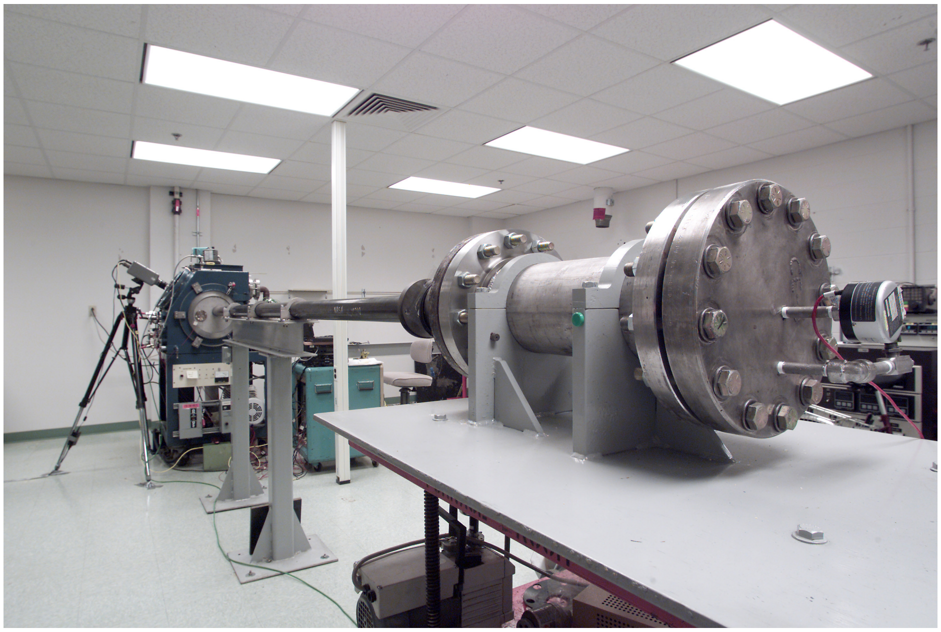

Figure 4.—Single stage gas gun showing pressure vessel in the foreground and barrel inserted into vacuum chamber.

The impact tests were conducted in a vacuum chamber under atmospheric conditions of 0.7 psia. The projectiles were accelerated by a single stage gas gun that consisted of a pressure vessel with a volume of $0.33ft^3$, and a gun barrel with a length of 12 ft and an inner diameter of 2.0 in. (fig. 4). The gun barrel projected into the vacuum chamber and the connection was sealed with an O-ring at the interface between the gun barrel and the vacuum chamber. The projectiles were supported by rigid foam in a polycarbonate sabot (fig. 2) which acted as a carrier and formed a tight seal with the inside of the gun barrel through the use of a pair of O-rings. The sabot was accelerated down the gun barrel by the release of helium gas from the pressure vessel which used a polyester burst disk as its release mechanism. The sabot was stopped at the end of the gun barrel at a position where the back of the sabot remained within the barrel creating a seal and preventing the helium propellant from entering the vacuum chamber, thereby maintaining the vacuum.

The impact force was transmitted through a circular sensor plate with a diameter of 2.5 in. and a thickness of 0.75 in. mounted on a piezoelectric load cell (PCB 260A13) (fig. 5). The load cell assembly was mounted on an aluminum block fixture in two configurations, one in which the ice impacted the plate at a normal incidence and the other in which the ice struck the plate at an angle of 45° (fig. 5). The load cell was conditioned by a charge amplifier (Kistler model 5010) with the output voltage subsequently passed through a 25 KHz anti-aliasing filter and recorded at a rate of 125,000 samples/sec by a digital data acquisition system (IOTECH Wavebook/516e). As will be seen, it was not possible to eliminate all of the resonances and no further filtering was performed as it was felt that it would compromise the measured force data. Attempts to simulate these tests therefore require some modeling of the fixture system for accurate comparison. Tests were conducted at impact velocities in the range of 300 to 800 ft/sec.

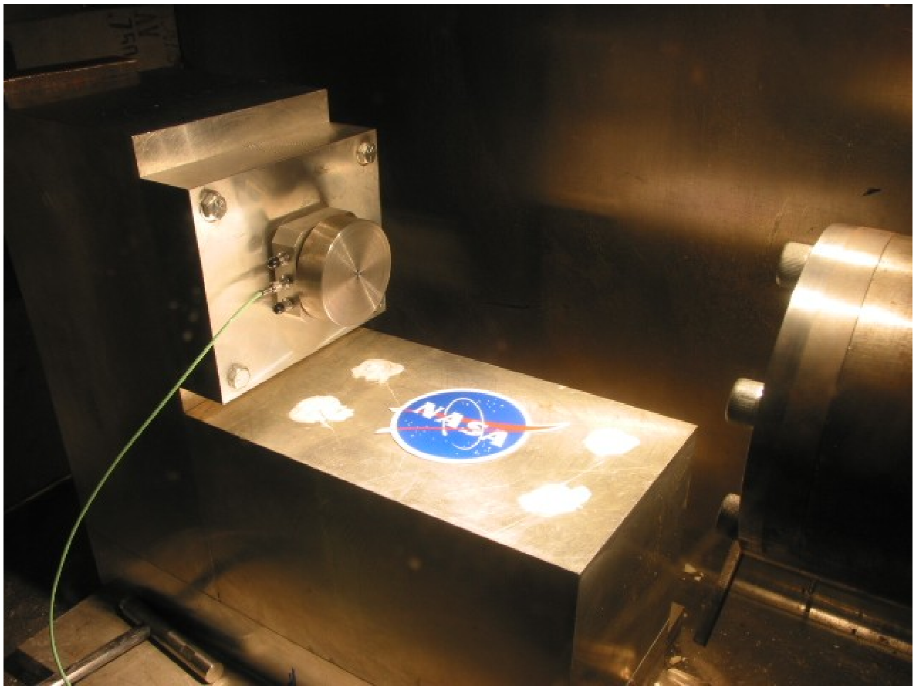

Figure 5.—90° load measurement system consisting of a mass supported on a piezoelectric load cell.

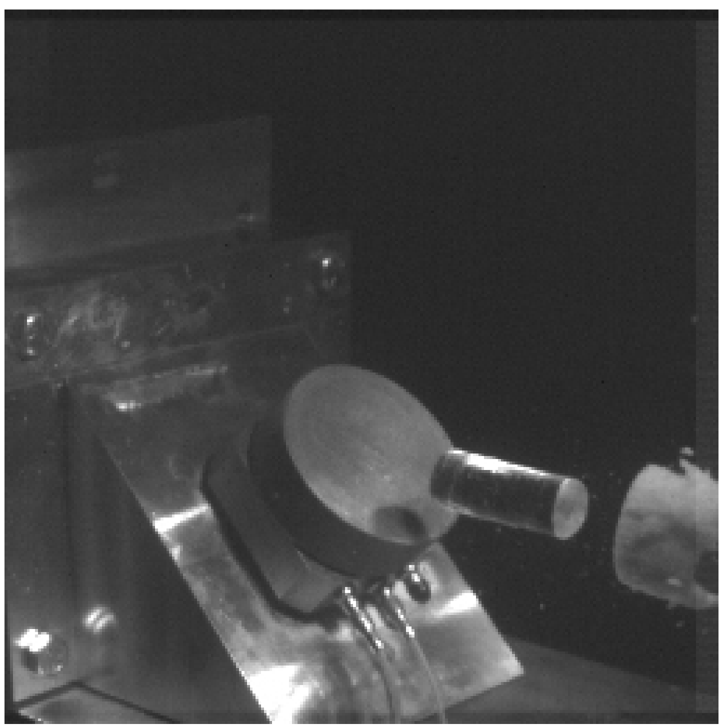

Figure 6.—Image from high speed video showing solid ice projectile moving toward 45° load measurement system. A portion of the foam support can be seen behind the projectile.

Prior to testing, the specimens were stored in their sabots in a sealed bag at a temperature of –20 °C. Initial tests were conducted to measure the temperature of the ice, using thermocouples inserted between the ice projectile and the sabot, as a function of time after removing the sabot and projectile from the freezer. It was determined that if the test took place within 5 min of removing the projectile from the freezer the ice temperature would remain in the range of –10 and –20 °C. All subsequent tests were conducted such that the predetermined time duration was not exceeded.

Results

A typical power spectrum of the measured force from a 90° impact test with a solid ice projectile is shown in figure 7. There are resonances at frequencies of approximately 4,400, 6,500, and 13,000 Hz. While filtering is possible to remove these resonances, other than the 25 kHz analog anti-aliasing filter, the data reported here is in its unfiltered form.

Effects of Crystalline Structure

Figures 8 to 10 show the transient response for the SX, PX and RPX ice at impact velocities of 300, 500, and 700 ft/sec, respectively. The legends refer to test numbers described in table 1. As can be seen in the figures, no discernable differences in the force response were observed as a result of differences in crystalline structure. This result supports the premise that the mass of the projectile is more important in determining the force transmitted through impact than the difference in strength due to the crystalline structure.

Figures 11 and 12 show the transient force response from tests on the 45° fixture at approximately 500 and 700 ft/sec, respectively, using RPX ice. This fixture has a resonance at approximately 6,700 Hz. The data is highly repeatable from test to test and the normal force is significantly greater than the shear force as would be expected due to limited friction.

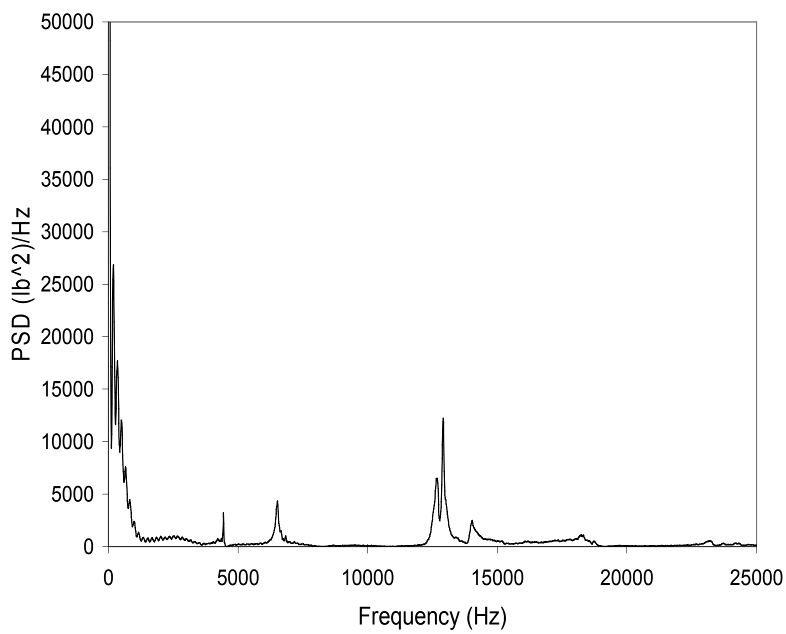

Figure 7.—Power spectrum of measured force from a typical 90° ice impact test.

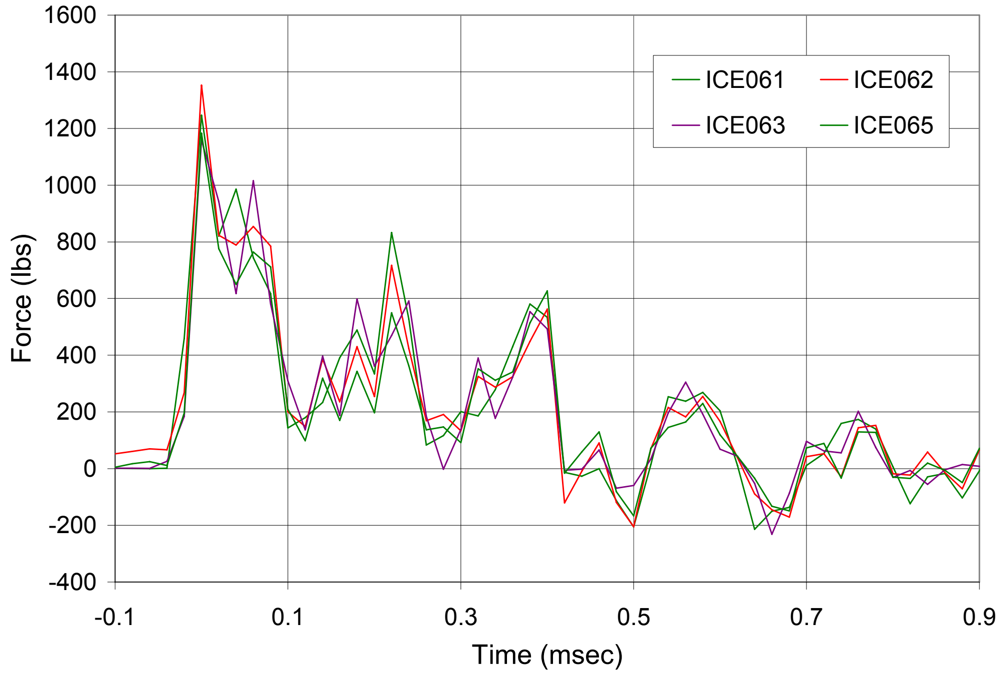

Figure 8.—Measured force from 90° impact tests. Solid ice at approximately 300 ft/sec.

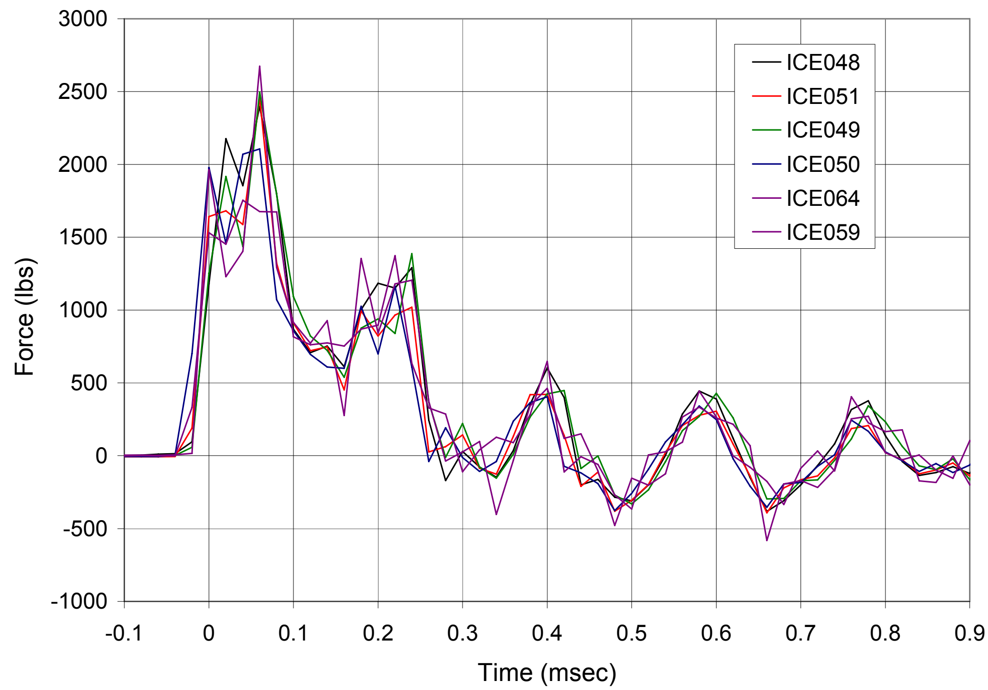

Figure 9.—Measured force from 90° impact tests. Solid ice at approximately 500 ft/sec.
Test conditions shown in table 1.

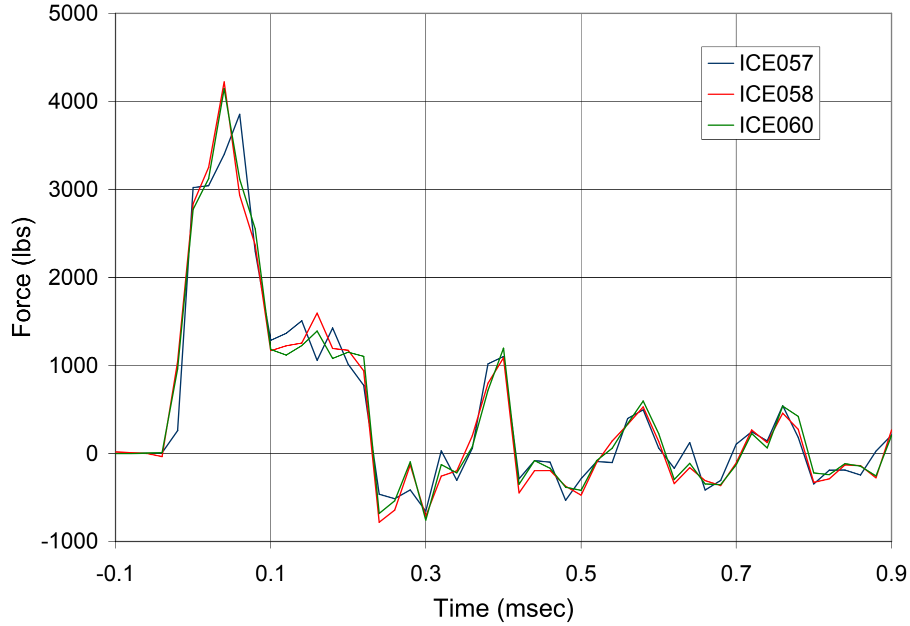

Figure 10.—Measured force from 90° impact tests. Solid ice at approximately 700 ft/sec. Test conditions shown in table 1.

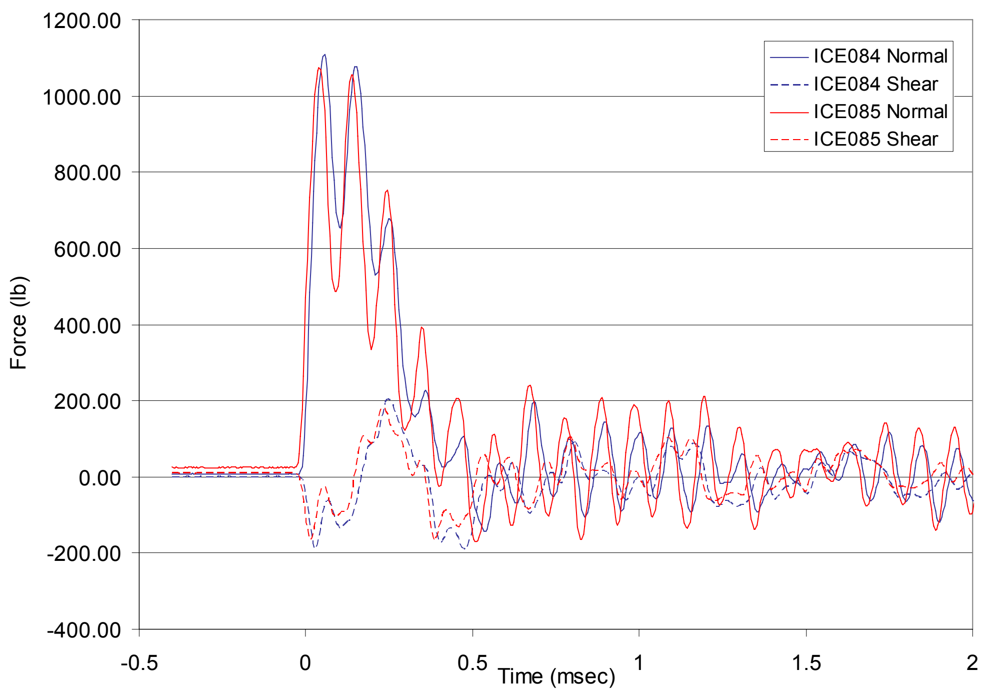

Figure 11.—Measured force from 45° impact tests. Solid ice at approximately 500 ft/sec. Test conditions shown in table 1.

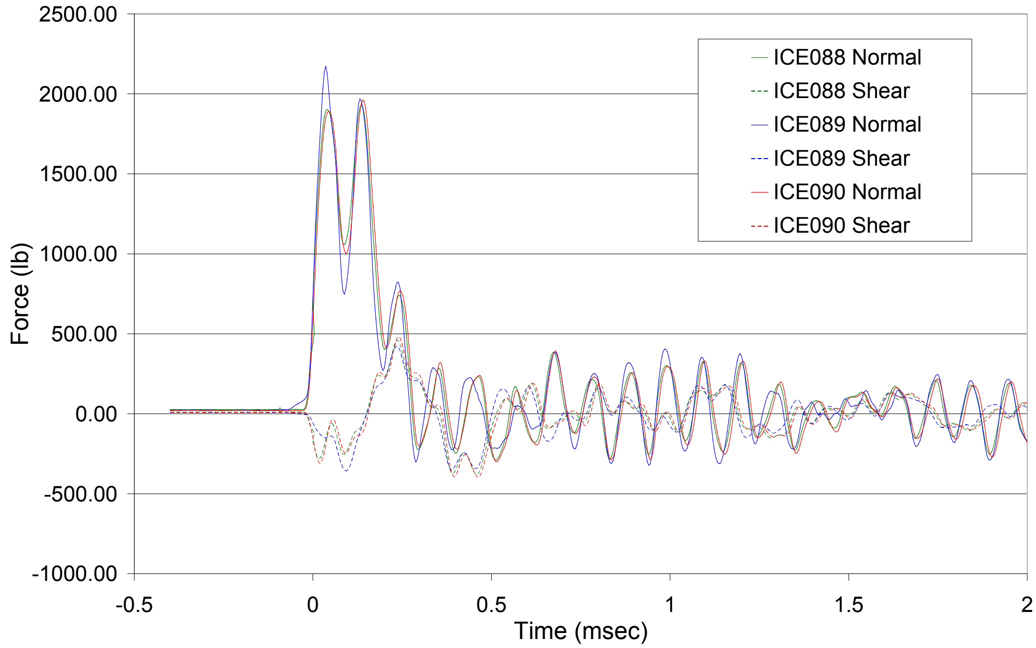

Figure 12.—Measured force from 45° impact tests. Solid ice at approximately 700 ft/sec. Test conditions shown in table 1.

TABLE 1.—TEST CONDITIONS FOR FULL DENSITY ICE TESTS

Test ID	Ice description	Projectile diameter, in.	Projectile length, in.	Projectile mass, g	Impact velocity, ft/sec
ICE048	RPX	0.678	1.66	8.87	521
ICE049	SX	.680	↓	9.01	504
ICE050	PX	.679		8.94	497
ICE051	RPX	.680		9.09	497
ICE057	RPX	.674		8.83	699
ICE058	PX	.678		8.92	699
ICE059	PX[1]	.678		8.95	492
ICE060	SX	.677		8.83	698
ICE061	SX	.680		8.95	315
ICE062	PX	.678		8.97	325
ICE063	RPX	.680		9.01	309
ICE064	SX	.677		8.92	497
ICE065	SX[2]	.676		8.92	296
ICE084	RPX	.688		8.72	494
ICE085	RPX	.688		8.58	482
ICE088	RPX	.688		8.56	722
ICE089	RPX	.688		8.70	707
ICE090	RPX	.688	↓	8059	700

[1]Projectile broke into two pieces prior to impact
[2]Fracture on front face of projectile prior to impact

Solid Ice Versus Low Density Ice

The forces measured in 90° impact tests using solid ice and low density ice are shown in figures 12 and 13 and the conditions corresponding to these tests are given in table 2. Within the scatter of the test results there is not a significant difference in forces. It should be noted that the mass of the low density ice projectiles averaged approximately 9 percent higher than that of the full density projectiles.

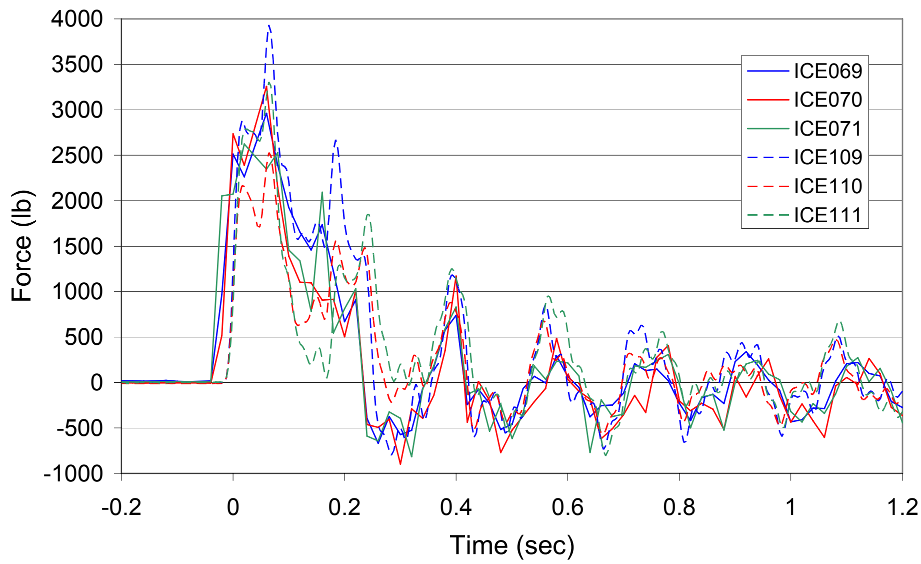

Figure 13.—Measured force from 90° impact tests with solid and low density ice. Tests conducted at approximately 700 ft/sec.

TABLE 2.—CONDITIONS FOR IMPACT TESTS COMPARING LOW DENSITY ICE TO FULL DENSITY ICE

Test ID	Ice description	Projectile diameter, in.	Projectile mass, g	Impact velocity, ft/sec
ICE069	RPX, solid	0.69	8.66	690
ICE070	RPX, solid	.69	8.72	684
ICE071	RPX, solid	.69	8.71	697
ICE0109	Low density	.8	9.55	696
ICE0110	Low density	.8	9.42	706
ICE0111	Low density	.8	9.50	701

Summary

As mentioned previously, when the impact velocity is significantly lower than the wave propagation speed, from a visual perspective the ice projectile acts like an agglomeration of many tiny ice particles rather than a single solid. It would appear that the normal mechanical characteristics of the ice have little effect on the observed transient response once the initial contact pressure subsides. Because of the very short duration of the initial impact force which causes fracture to initiate in the ice, its measurement requires a system with extremely high frequency response. Capturing this portion of the response was found to be very difficult with the conventional force measurement instrumentation used in this study. The data presented here show the forces generated by different forms of ice after the initial contact pressure has relaxed. In the impact velocity range considered here, the results indicate that the crystalline structure of the ice has negligible effects on the forces generated during impact.

Similarly, the impact forces generated by the low density ice projectiles, which has very low mechanical strength, are comparable to those of full density solid ice. This supports the hypothesis that at a velocity significantly greater than that required to produce fracture in the ice, the mechanical properties become relatively insignificant, and the impact forces are governed by the shape and mass of the projectile.

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13. ABSTRACT *(Maximum 200 words)*

Tests were conducted to measure the impact forces generated by cylindrical ice projectiles striking a relatively rigid target. Two types of ice projectiles were used, solid clear ice and lower density fabricated ice. Three forms of solid clear ice were tested: single crystal, poly-crystal, and “rejected” poly-crystal (poly-crystal ice in which defects were detected during inspection.) The solid ice had a density of approximately 56 lb/ft^3 (0.9 gm/cm^3). A second set of test specimens, termed “low density ice” was manufactured by molding shaved ice into a cylindrical die to produce ice with a density of approximately 40 lb/ ft^3 (0.65 gm/cm^3). Both the static mechanical characteristics and the crystalline structure of the ice were found to have little effect on the observed transient response. The impact forces generated by low density ice projectiles, which had very low mechanical strength, were comparable to those of full density solid ice. This supports the hypothesis that at a velocity significantly greater than that required to produce fracture in the ice, the mechanical properties become relatively insignificant, and the impact forces are governed by the shape and mass of the projectile.

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